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Review

Water Quality Improvement Performance of Geotextiles Within Permeable Pavement Systems: A Critical Review

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Abstract: Sustainable drainage systems (SuDS; or best management practices) are increasingly being used as ecological engineering techniques to prevent the contamination of receiving watercourses and groundwater. Permeable paving is a SuDS technique, which is commonplace in car parks, driveways and minor roads where one of their functions is to improve the quality of urban runoff. However, little is known about the water quality benefits of incorporating an upper geotextile within the paving structure. The review focuses on five different categories of pollutants: organic matter, nutrients, heavy metals, motor oils, suspended solids originating from street dust, and chloride. The paper critically assesses results from previous international tests and draws conclusions on the scientific rigour and significance of the data. Findings indicate that only very few studies have been undertaken to address the role of geotextiles directly. All indications are that the presence of a geotextile leads only to minor water quality improvements. For example, suspended solids are being held back by the geotextile and these solids sometimes contain organic matter, nutrients and heavy metals. However, most studies were inconclusive and data were often unsuitable for further statistical analysis. Further long-term research on industry-relevant, and statistically and scientifically sound, experimental set-ups is recommended.

Keywords: best management practice; car park; clogging; heavy metals; oil; paving block; pollutant removal; salt; suspended solids; sustainable drainage system

1. Introduction

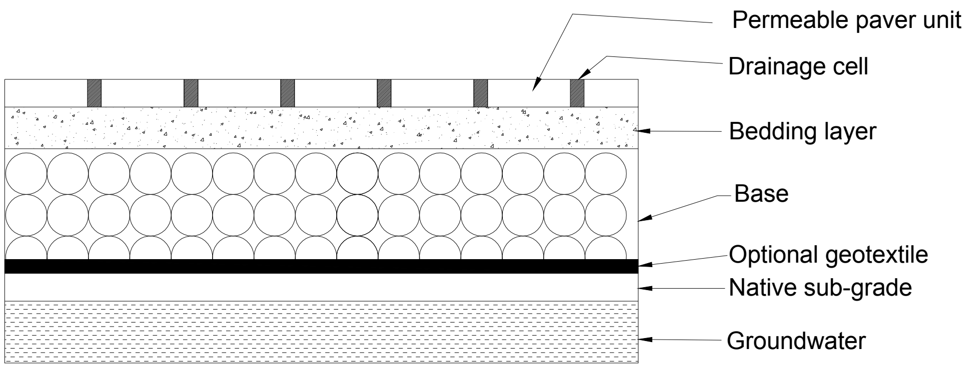
1.1. Background

The runoff from urban areas carries various pollutants including organic matter, nutrients, heavy metals, oils and suspended solids, which have previously been deposited onto impermeable surfaces. The majority of pollution in urban runoff originates from diffuse sources (often difficult to identify) including traffic emissions, decomposing litter, salts, building materials and soil losses [1,2]. These pollutants pose a risk to the urban watercourse quality and to the soil, if they remain untreated.

The management of storm water with Sustainable drainage systems (SuDS) such as permeable pavements, ponds and swales can have a positive effect in reducing these pollutants and delaying the volume of water discharging to the sewer or receiving water body. However, SuDS are frequently difficult to retrofit and implement on a large scale due to space and cost constraints. The change from permeable to impermeable land (e.g., roofs, roads and pavements) reduces groundwater recharge and creates a large volume of runoff and a higher peak flow rate in the drainage system. This can often lead to urban flooding, particularly during heavy rainfall and when sewers operate at their full capacity [1,2].

The SuDS technique ‘permeable pavement’ has become a popular solution in reducing the burden of increased runoff by restoring the infiltration treated runoff (if desired), water quality improvement and hydraulic functions of natural systems [3]. Permeable pavement systems vary greatly in terms of type, construction, dimensions, operation and management. An example of a permeable pavement system is shown in Figure 1.

Figure 1. Schematic outline of the main design components of a permeable pavement system.



Environment agencies such as the Scottish Environment Protection Agency (SEPA) usually accept permeable paving surfaces as SuDS techniques. For example, SEPA’s considerations for acceptance of surface drainage systems must be in line with the “General Binding Rules” contained within “The Water Environment (Controlled Activities) (Scotland) Regulation” [4]. For new developments, surface water must drain through a SuDS system if discharged into the environment and all “reasonable steps” should be taken to ensure that the discharge shall not result in pollution to the water environment. The use of proprietary permeable paving systems with a geotextile and a cellular (or modular attenuation system) meets this requirement where a single level of treatment is a requirement (e.g., small housing developments).

For situations such as commercial and retail sites, SEPA considers that two levels of treatment are required and as such a washed stone-filled sub-base below a proprietary paving system and in conjunction with a geotextile, preventing fines from entering the sub-base, would provide two levels of treatment. Such an arrangement would deliver the requirement for "reasonable steps" [4] to be taken to protect the water environment. This would assume that an adequate depth of sub-base is provided to allow filtration through a washed stone-filled sub-base.

With respect to the case study areas located in Scotland (Sections 4 and 5), SEPA works on the assumption that the presence of any geotextile within a standard permeable pavement system has a water quality improvement function [5]. However, no specific scientific evidence has been officially referenced by SEPA to avoid creating the impression that the agency favors a particular commercial product.

1.2. Rationale, Aim and Objectives

Very few ecological engineering research studies on permeable pavement systems produce directly comparable water quality results for paving constructions with and without an upper geotextile layer. Therefore, this paper aims to critically analyse research studies undertaken to determine the role of a geotextile layer in pollution control. The objectives are:

- To conduct a review of geotextiles within the SuDS context;
- To briefly assess recent permeable pavement system research;
- To critically review selected research projects on geotextiles within permeable pavement systems undertaken for the concrete and aggregate industry;
- To draw conclusions based on the critical literature review; and
- To recommend further research work.

International ecological engineering research has been reviewed. However, a specific focus is on case studies with relevance to areas experiencing temperate and oceanic climates. This includes most parts of Northern America and Europe. Such a restriction in focus is necessary because environmental boundary conditions vary greatly across the globe. Only a few recent studies directly concerned with the geotextile and water quality were identified in the literature review comprising more than 200 documents. Therefore, Sections 4 and 5 focus on these relevant research studies addressing the role of geotextiles with respect to pollution control.

2. Critical Review of Geotextiles in the Context of Permeable Pavements

2.1. Relevant Types of Geotextiles

Geotextiles can be characterised as being either woven or non-woven. Most woven geotextiles are formed by interlacing two or more sets of yarns, fibers or filaments where they pass each other at right angles [6]. Specific weaving methods create four main types of geotextiles: monofilament, slit film, multifilament and fibrillated. Monofilament geotextiles offer little resistance to through-flow of water and are generally made from polyethylene (HDPE) or polypropylene (PP). Standard geotextiles are semi-inert materials with predominantly physical properties [1], which are relevant in the context of this review paper.

A multifilament yarn consists of many fine continuous filaments that are held together by twisting of the strands. Fibrillated tapes are made by splitting and twisting extruded films. Woven slit films are produced with yarns formed by longitudinally splitting of a polymeric film to form a slit tape yarn. However, this type of woven geotextile is not suitable for most drainage and filtration applications [7].

Woven geotextiles are characterized by their excellent strength properties and are generally less expensive than non-woven types of the same strength [6]. Non-woven geotextiles are typically manufactured by putting small fibers together in the form of a sheet or web, and then binding them by mechanical, chemical and/or solvent means. They are usually grouped into three categories: needle punched, chemical bonded or heat bonded [6].

Non-woven geotextiles are generally not as strong as their equivalent woven geotextiles, but they exhibit better filtration and separation properties [8]. For this reason, nonwoven geotextiles are the preferred geotextile type for permeable paving applications.

The polymers used to construct both woven and non-woven geotextiles are synthetic polymers (polyester, polypropylene or a mixture of polyester and polypropylene). Polyester and polyolefins such as polypropylene are hydrophobic materials. Whilst this is advantageous in circumstances that require water and/or suspended solids to be trapped above the surface of the geotextile, it may lead to ponding within a permeable pavement structure, if geotextiles with the incorrect flow rate and permittivity are being used. Polyesters and polypropylene materials are highly resistant to chemical and biological degradation [6] and therefore suitable for application in the construction industry.

The majority of manufacturers use polypropylene in the construction of their geotextiles, because polyester deteriorates over time under both acidic and alkaline conditions. However, the degradation is more severe under alkaline conditions, which are rarely the case in urban runoff [2,9].

2.2. Geotextile Applications and Their Properties of Relevance for Permeable Pavements

Geotextiles can be used for the separation and strengthening layer under new roads and car parks, and as a filter in certain SuDS applications including permeable pavements and infiltration trenches. Geotextiles can also enhance organic matter (e.g., leaf litter and hydrocarbons) removal by trapping the contaminants on the surface cavities, then allowing microbial biodegradation to occur [10]. Moreover, geotextiles may support drainage but there are potential problems with frost in cold climatic regions such as Scotland and Canada [11].

Pavement engineers concerned with assessing geotextile properties may refer to Jersey and Tingle [12]. Behavioural trends were characterised for geotextile material types and manufacturing processes. The implications of the trends for design applications and product specification were noted. However, no specific reference to water quality improvement issues has been made.

The functions of geotextiles are usually divided into five main categories: separation, filtration, drainage, protection and reinforcement. With respect to the case studies discussed in Sections 4 and 5, British guidance on the properties of geotextiles for use in drainage systems and in trafficked areas is given in BS EN 13252:2001 [13] and BS EN 13249:2001 [14]. These standards have subsequently been interpreted by the concrete and aggregate industry operating in Britain (e.g., [2]).

The ability of a geotextile to retain fines (e.g., suspended solids) depends primarily on its opening size [15]. The Pore Size (or Characteristic Opening Size) Test is designed to assess the mean size of the holes in the fabric. The gap sizes for common geotextiles vary widely between 70 and 380 microns. The 85% size of soil is compared with the apparent opening size of geotextiles. The apparent opening size refers to the approximate largest opening dimension available for soil to pass through it. The findings indicate that for sand and silt size particles, a geotextile with apparent opening size (O-95) less than 85% size [d(85)] of retained soil would perform satisfactorily. However, for fine soils in suspension, the ratio of geotextile O-95 to soil d(85) should be restricted to 0.5 or less. This recommendation helps to select the most appropriate geotextile when designing for water quality improvement.

Permeability tests for geotextiles may differ between 36 and 120 L/(m^2s), and are generally a function of the weight and thickness of the geotextile [16]. This test is of great relevance when assessing the suitability of a geotextile for its suspended solids retention potential within a permeable pavement system. A further discussion on permeability test results as a function of opening sizes, materials and test standard conditions is beyond the scope of this paper, which focuses on water quality issues (see Sections 4 and 5).

The presence of a geotextile layer on top of the base of the permeable pavement parking lot structure (experimental case study example) is one key factor restricting vertical percolation to the deeper parts of the permeable pavement system [9]. Clogging of the permeable surface due to the accumulation of suspended solids was most pronounced in heavy traffic areas and below snow pile storage areas. Corroborated by high electric conductivity and chloride measurements, sand brought in by cars during winter was the principal cause for clogging. The study clearly highlighted the limitations of the geotextile properties during extreme conditions.

3. Assessment of Permeable Pavement Systems

3.1. Need for a Permeable Pavement Systems Review

A typical permeable pavement consists of a permeable paving layer, bedding layer, base and sub-base [17]. Building and environment geotextiles are generally placed at one or two levels within permeable paving structures; at the upper level separating the bedding layer and sub-base; and/or at the lower level separating the sub-base from the sub-grade. A geotextile layer is usually placed between the bedding layer and the base to increase the structural integrity (if the infiltrating runoff is relatively free from particles), pollutant retention capabilities and biodegradation processes for organic contamination within the pavement systems [18].

The geotextile layer also encourages microbial activity in this area, leading to an improved treatment of runoff due to biological degradation processes [10,18]. Furthermore, the geotextile also prevents fine particles (partly responsible for clogging) in the bedding layer from moving downwards into the aggregate, subsequently creating air pockets within the bedding layer, contributing to a potentially structurally unstable surface [17].

With direct relevance to the case studies discussed in Sections 4 and 5, various researchers in the UK (e.g., [17,19]) and SEPA [5] have made claims implicitly or explicitly that a geotextile is needed to achieve good environmental performance. However, there is a current debate particularly amongst civil engineers and representatives from the concrete and aggregate industry about the water quality benefits gained by incorporating an upper geotextile.

This review paper covers a wide range of assessed literature including more than 150 relevant ISI Web of Knowledge-listed journal papers contributing to this discussion. It is evident that a large number of international studies have been conducted on the pollution removal efficiency of permeable pavements, their hydraulic properties and the effect of clogging. However, the literature review indicates that only a relatively small number of these experiments included an upper geotextile layer (e.g., [20–22]). The removal processes of key contaminants within various permeable pavement systems are reviewed in the following sub-sections to clarify their role in terms of water quality improvement.

3.2. Removal of Heavy Metals

The quality of runoff waters from porous pavements has been studied by Legret *et al.* [23]. The filtration effect of runoff by the reservoir structure incorporated within the pavement system decreased the pollutant concentrations by about 64% for suspended solids (often associated with adsorbed metals) and 79% for lead. Most metallic micro-pollutants (lead, copper, cadmium and zinc) accumulated on the surface of the pervious asphalt. A smaller proportion of these pollutants also accumulates at the level of the geotextile layer separating the structure from the underlying soil.

A comparison between the runoff quality from asphalt, crushed stone and paver driveways has been undertaken in Connecticut, USA [24]. The study was, however, inconclusive regarding the potential impact of a geotextile. A further study [25] evaluated the pollution retention capacity of a paving area for lead, zinc, cadmium and copper in Germany. Five laboratory rigs, each containing different joint fillers, showed high retention abilities for all metals. It was found that the overall removal efficiencies for cadmium, lead, copper and zinc were 99%, 99%, 98% and 94%, respectively.

3.3. Removal of Oils

A study concerning two rigs was published by [26]; one rig had an upper geotextile and another "virtually identical" rig had no geotextile. The presence of an upper geotextile was found to be important during oil retention studies. Furthermore, both a laboratory and a field study to simulate crank case leakage have been conducted previously [27]. The apparatus contained both an upper and lower geotextile. It was observed from the experiment that only 2.4% of the oil applied is not retained within the system. A further study [28] by the same research group indicated that a permeable pavement structure's efficiency in degrading oil was a function of nutrient supply. The authors found that permeable paving systems were associated with high oil removal rates of 99.6%.

Geotextiles incorporating inorganic nutrients to enhance the growth of oil-degrading micro-organisms when geotextiles are used in pervious pavement applications have been shown to be effective in previous studies [28]. A relatively low-cost polypropylene random mat geotextile incorporating an alternative polymer additive as a source of phosphorus has been investigated as a potential self-fertilising geotextile. Initial findings regarding nutrient leach rates, biofilm formation and biodegradation activity were positive. Biofilm formation on the geotextile layer improves the water quality due to biodegradation of contaminants such as oils.

Bio-degradation by microbial communities in three differently sized permeable pavement structures, each with different concentrations of oil applied per week, was studied by [29]. All rigs were constructed with an upper geotextile. Some of the rigs were inoculated with Biothreat HD, an oil degrading microbial inoculum, and some of the rigs also had a slow release fertiliser added to them. Oil was applied using a dripper to simulate vehicle engine leakage. Both the large and the medium rigs (inoculated or not), retained 99% of the oil applied. For medium-sized rigs, the amount of oil on the geotextile was slightly less for non-inoculated rigs compared to inoculated rigs (8.9% to 9.9%). However, no reference has been made with respect to the proportions that were removed by biodegradation and evaporation.

3.4. Removal of Suspended Solids

Geotextiles with fine pores should be able to retain fines including suspended solids (see above). The accumulation of water on a permeable pavement layer, also called ponding, is often a result of a clogged system due to the presence of too many suspended solids. Researchers compared the ponding depths on different permeable paving surfaces [30,31]. The depth of ponding indicated the severity of clogging. Clogged geotextiles clearly limited infiltration. Furthermore, when comparing asphalt, block paving and crushed stone driveways with each other, the infiltration rates were 0.0, 11.2 and 9.0 cm/h, respectively [24]. Moreover, infiltration rates for both block paving and crushed stone driveways declined over the course of this study. The reason for this observation is pore clogging by suspended solids. It follows that it is important to select a pavement material type that would not lead to the clogging of the geotextile within the same system.

The processes and characteristics of solids removal in two types of permeable pavements were assessed in Canada [32]: UNI Eco-Stone and porous asphalt. Results from the study showed that both pavement types are capable of excellent suspended solids removal (90% to 96%). Laboratory results indicated that, although solids removal occurs throughout the entire structure, the sieving action occurs primarily at the geotextile interface, confirming findings from other reviewed studies.

Different types of pervious pavements were tested in Northern Spain [33–35]. Pervious surface materials had a greater effect than the geotextile layer in terms of water quality improvements. The treated water could be harvested and recycled. Nevertheless, the researchers state that the differences in terms of storm water management using the different pervious pavement types tested still need to be confirmed in further more specific studies regarding the impact of the geotextile on water quality [33].

3.5. Removal of Other Parameters

This section covers water quality parameter that are only of interest under specific circumstances. There is little direct focus on the removal of other parameters such as organic matter, nutrients and chloride (due to road salting), and the interactions between different contaminants such as herbicides and hydrocarbons. Particles containing organic matter and nutrients are being partly retained by the geotextile. However, the majority of the solids is dissolved, and they are therefore simply being washed through the geotextile [1,2].

Road gritting and salting has been identified as a major water quality problem in countries with cold regions such as Canada, UK, Scotland, Germany and Sweden (e.g., [36]). The application of grit mixed with salts usually contributes to elevated suspended solids concentrations, and high conductivity, salt and chloride values [1,36]. Road salts are usually washed through the permeable pavement system with a negative impact on the biomass growth [1]. Conductivity values are not affected significantly by the presence of a geotextile [9]. Therefore, very little chloride is retained by the geotextile layer [1,2,22].

Finally, a recent experimental investigation was carried out to determine the effect of glyphosate-containing herbicides on the hydrocarbon retention and biodegradation processes known to occur in permeable pavement systems [37]. Findings indicated that glyphosate-containing herbicides disrupted hydrocarbon retention by geotextiles.

4. Critical Review of the "Abertay Study"

4.1. Essential Background

This section is concerned with the critical review of a research study [38,39] on the role of a geotextile in permeable pavement systems undertaken by the University of Abertay. The study focused on assessing the impact of a geotextile on removing selected heavy metals, oil and suspended solids. The metal concentrations applied were twice the typical values for polluted highway runoff [40]. The oil contamination levels were based on a previous publication [19]. Moreover, suspended solids contamination levels followed those reported previously [41]. However, these data refer to Australian studies, which might not be representative for this Scottish case study.

4.2. Summary of Methodology

Researchers report on ten above-ground (not insulated) test rigs with dimensions of 1 m length × 1 m width × 0.5 m depth, which were constructed at a test site near Dundee in Scotland (Figure 2) [38,39]. The test rigs were designed in accordance with the standard specifications used by Marshalls for their Priora Paving system incorporating the non-woven geotextile Terram 1000 (produced by Terram, The Causeway, Maldon, Essex CM9 4GG, England, UK). The design methodology and base specifications were in accordance with BS EN 13242:2002 + A1:2007 [42] and BS 7533-13:2009 [43].

Rainfall was simulated using a branch sprinkler system. Three different categories of pollutants were applied: metals, oils and suspended solids obtained from street surfaces. Water samples were taken from sample pots every two minutes using Epic automatic samplers. Three composite samples were used for analysis.

Contaminant loads representing a total of 10 years were applied to the test rigs in batches of 1, 2 and 7 years [38,39]. An 'accelerated' timescale was applied for the tests. The estimated load of pollutants for each of the time periods (1, 2 and 7 years) was applied with one year of rainfall (1200 mm) over 100 min. In the case of street dust, a total of 20 years was applied in batches of 3, 3, 4, 5 and 5 years.

The metals were obtained from suppliers already in solution at the required concentrations. A concentrated solution containing a 'cocktail' of metals was added to the appropriate water tanks. The content of the water tank (Figure 2) was then mixed before the solution was applied to the paving area using the sprinkler system.

Figure 2. Main experimental set-up used in the "Abertay study" (picture provided by Marshalls).

Light motor oil (10W/40) was used to best represent oil drips from modern cars. Oil was dripped onto the paving area using a bucket with holes in the base. The equivalent of one year of oil load was applied before starting the rainfall simulation. In the case of the equivalent of two years of oil load, hydrocarbon was applied in two batches; the first batch before the test run began followed by the second one after 45 min into the test run. The water was turned off to allow the oil to be dripped onto the pavement. The remaining water volume was subsequently sprinkled onto the pavers. For the seven-year duration simulation run, the water was stopped every 15 min to allow the equivalent of one year of oil to be applied. Once the oil had been used, the rainfall simulator was placed back onto the paving unit and water was sprinkled for another 15 min, until the equivalent of seven years of oil load had been applied.

Street dust was spread onto the paving area evenly and washed into the gaps between the pavers using 15 L of water from a watering can. The annual rainfall volume was then applied using the rainfall simulator. For test runs using the corresponding five years of sediment load, street dust was applied in two batches at 90° angles to one another. The weight of each batch was 550 g.

4.3. Review of Key Findings

Results from the application of one year equivalent of metal loads showed varied metal removal rates [38,39]. After the application of the equivalent of three years of metals, the removal rates of cadmium, zinc and lead were higher (*i.e.*, between 2% and 5%) in rigs, which included a geotextile layer than those without. Copper elimination rates were generally low. Nickel removal rates were high in the test rig with a geotextile.

After the equivalent of ten years of metals had been applied, all metals (cadmium, copper, lead, zinc and nickel) showed higher removal (between 2% and 6%) rates for the rig, which contained an upper geotextile. However, the measurement error was estimated to be high and a statistical analysis was not undertaken [38,39].

Oil removal rates for all test rigs were above 90% at the end of the simulation for year one confirming related findings [28]. Test rigs with a geotextile removed slightly higher amounts of hydrocarbon. For the simulation of year two, the oil-only rig with a geotextile removed a greater proportion (approximately 10%) than the equivalent rig without a geotextile. The rig receiving metals and oil without a geotextile had slightly higher oil removal efficiencies (approximately 4%) than the comparable rig without the geotextile. After the equivalent of ten years of oil had been applied to the test rigs, the rig receiving metals and oil and containing a geotextile had removed 13% more oil than the other test rigs. In contrast, there was no difference in the removal of oil in the two oil-only rigs. The results indicate no clear evidence that the presence of a geotextile had an impact on the removal of oils.

The application of street dust to the paving units caused increased ponding and overflowing as the sediment mass applied increased. Findings confirmed those reported earlier [28]. Moreover, in the two runs representing the equivalent of three and six years of street dust, there was minimal interference with the flow of water through the paving system. After the equivalent of ten years of application, both test rigs showed significantly more ponding during the watering stage, and larger agglomerations of sediment were left in the gaps between the pavers after watering in comparison to previous runs. After simulating year 15, sediment agglomerations on the surfaces of the pavers were even greater than in previous test runs. This resulted in reduced flow rates indicating blockage. For year 20, the rigs failed due to complete clogging.

4.4. Summary of the Conclusions

The results for year three showed insignificantly higher metal removal rates for cadmium, lead and zinc when the geotextile was present. Test rigs with a geotextile performed best after the application of the equivalent of 10 years of metals.

Oil removal was greatest for the test rigs containing a geotextile after ten years of application. After three years of simulation concerning the oil-only experiments, the test rig containing a geotextile removed a greater proportion of oil. The rig receiving oil and metals with a geotextile removed slightly less than the corresponding non-geotextile test rig with results similar to that of the oil-only geotextile test rig. No statistical tests were performed. The presence of a geotextile had little impact on the removal of oil [38].

With respect to the street dust application, there was no evidence of any obvious impact on the water quality by including a geotextile. There was, however, great variability in the results for all rigs. There was insufficient information to conclude whether an upper geotextile is beneficial or not [38,39].

4.5. Critical Assessment of the '*Abertay Study*'

The experimental set-up [38,39] is impressive due to the high number of rigs and their relatively large size. However, the overall study was undertaken subject to the following conditions and assumptions:

- The test rigs were located above the ground (Figure 2), which exposed them to unrealistic environmental conditions such as high temperature fluctuations and enhanced wind exposure impacting on removal processes. In terms of water quality, removal rates are over-estimated during warm periods and under-estimated during cold periods.
- The simulation of multiple years of pollution represents the application of a series of severe one-off shock loads. Most pollutants were simply being forced hydraulically through the system, and very little biodegradation activities took place. Moreover, total metal adsorption is lower than under long-term test conditions. Accelerating loading by increasing contaminant concentrations also affects the corresponding sorption isotherms, which were not determined in this study.
- The combination of different pollution loads simulates worst case scenarios in parallel and in series. The testing period of about two months is too short to represent different seasons and allow representative biomass to mature in the systems.
- The hydraulic flow rate and both the loads and concentrations of most pollutants selected were too high.

Considering the above circumstances, the study may be viewed as applied research covering extreme scenarios in the 'real' world. Therefore, a clear judgment on the purification capacity that could be contributed to the geotextile cannot be made.

5. Critical Review of the 'Edinburgh Study'

5.1. Essential Background

This section is concerned with the critical review of a long-term and well-reported research study [3,10,22] undertaken by the The University of Edinburgh for Hanson Formpave (Hanson UK, 14 Castle Hill, Maidenhead SL6 4JJ, England, UK). Several types of combined permeable pavement and ground source heating pump systems used to treat urban runoff were evaluated. The study was originally designed to assess the effectiveness of removing urban runoff containing dog faeces and not the potential benefits associated with a geotextile.

5.2. Summary of Methodology

Two permeable pavement system (Figure 3; Table 1) rigs were operated under controlled and uncontrolled environmental conditions for more than three full calendar years [22]. An example experimental permeable pavement system incorporating a geothermal heating or cooling system is shown in Figure 3. The increase or decrease in temperature of the sub-base will either enhance or reduce microbial activity impacting therefore on the biodegradation activity of species.

Typical polyethylene 240-l wheelie-bins have been used as basic construction devices. The bins mimicked impermeable tanked systems (*i.e.*, no ground infiltration) and provided suitable conditions for water collection.

Figure 3. Schematic outline of the main design principles of an experimental permeable pavement set-up without and with a geothermal system used in the "Edinburgh study" (after [10]).

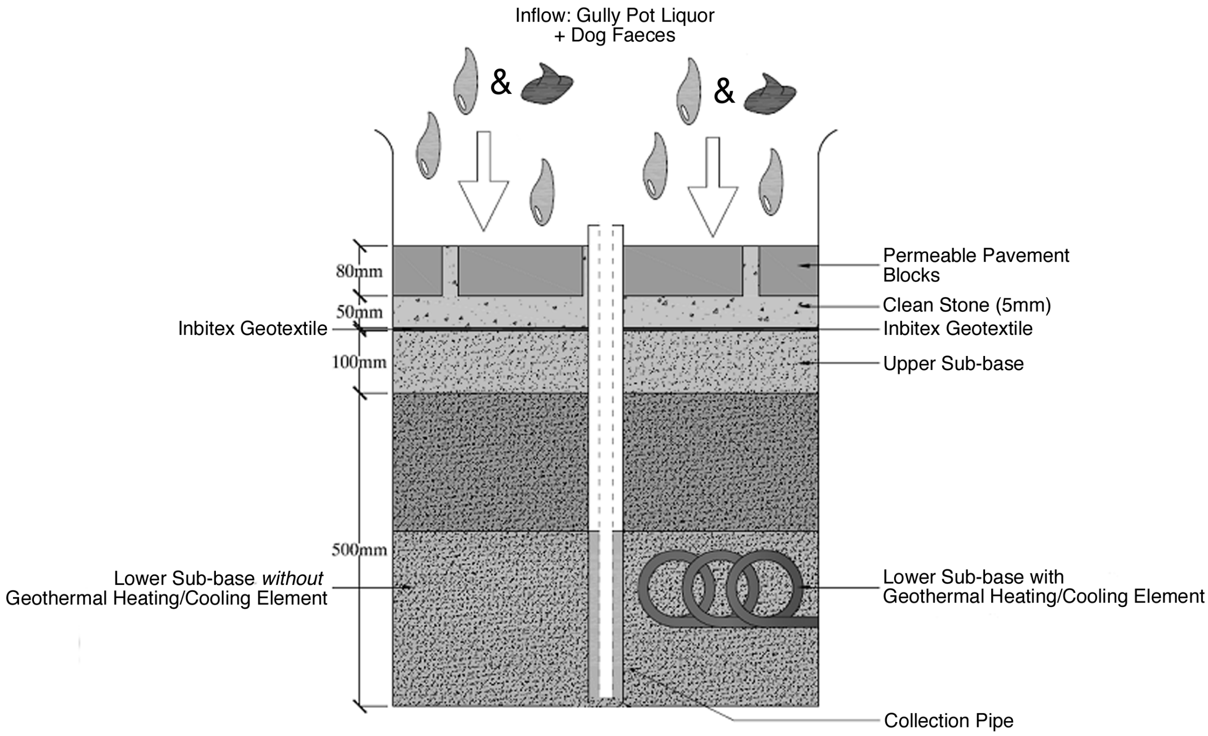


Table 1. Schematic layout of the experimental rigs of the Edinburgh study.

Feature	Bins of the inside rig						Bins of the outside rig					
	1	2	3	4	5	6	1	2	3	4	5	6
Inbitex composite	√	√	√				√	√	√			
Inbitex geotextile				√	√	√				√	√	√
Cooling or heating	√	√		√	√		√	√		√	√	
Animal feaces added	√			√			√			√		
Air thermometer	√				√	√	√				√	√
Vessel thermometer	√				√		√				√	
Carbon dioxide sampling point	√				√		√				√	

The indoor system was composed of six bins and placed in a temperature-controlled room with a mean ambient temperature of 16 °C. The outdoor rig was submerged within the ground and located outside the local laboratory building where atmospheric temperature conditions prevailed. All bins were partly filled with the inflow water, and operated in batch flow mode, which therefore simulates real car park and pavement runoff conditions better than a continuous flow mode.

Commercially available pre-washed aggregates were used for the construction of the sub-base. The porous Inbitex geotextile (Table 1), which is made of polyethylene and polypropylene fibres (see above) was placed in the top part of the upper-base, as this is the area where considerable microbial degradation of pollutants is expected to take place. Either Inbitex on its own or Inbitex together with an impermeable layer (Terram Drainage Composite), called composite, were used in the experiments

(Table 1). The impermeable layers were overlapped with each other to allow water to percolate through the system but to avoid evaporation.

Water was exchanged twice per week. The influent samples were prepared by collecting gully pot liquor and fresh dog faeces on the same day of analysis. Approximately 2.2 L of "outflow" sample water was slowly collected approximately 100 mm from the bottom of each bin by a hand lever pump. The temperature of the sample was immediately recorded at this stage. Finally, carbon dioxide samples were collected via collection tubes located at various depths within the bins.

5.3. Review of Key Findings

Because of the strong variability of the chosen pollutants, the standard deviation for suspended solids was 411 mg/L and 181 mg/L for the inflow water with and without additional pollutants, respectively. Similar observations were made for conductivity and ammonia-nitrogen. Road gritting and salting in winter leads to high fluctuations of suspended solids, conductivity and chloride concentrations [2,9].

Relatively stable and uniform values were only recorded for pH, DO and nitrate-nitrogen. The mean bin intakes for ortho-phosphate-phosphorus were 1.9 mg/L and 26.2 mg/L without and with dog faeces, respectively. The corresponding concentrations for ammonia-nitrogen were 14.7 mg/L and 39.3 mg/L, respectively.

The variability of pH was relatively low. In contrast, the maximum standard deviations for conductivity ranged between 25 and 80 μS for the inside and between 8 and 124 μS for the outside rig, respectively. Outdoor variability was usually greater than indoor (controlled environment) variability as expected. However, the most significant ($p < 0.002$) variability has been recorded for suspended solids with respect to the outside bin 5 and inside bin 2 (Table 1); corresponding standard deviations reached concentrations of 208 mg/L and 269 mg/L, respectively.

Mean dissolved oxygen concentrations were similar for both rigs: they were between 5 and 6 mg/L for the inside rig and between 5.5 and 7 mg/L for the outside set-up. Overall reductions in dissolved oxygen for both systems ranged between 22% and 46%. The BOD reductions ranged between 98% and 100%.

Concerning nutrients, high reductions in ortho-phosphate-phosphorus and ammonia-nitrogen were observed. For the inside system, ortho-phosphate-phosphorus concentrations were less than 1 mg/L (corresponding reduction of 95%). For the outside system, concentrations fluctuated between 0.2 mg/L and 0.6 mg/L with corresponding reduction rates of approximately 95%. Ammonia-nitrogen reductions were up to 100% for both systems and the corresponding concentrations ranged between 0.1 mg/L and 0.2 mg/L for the inside and between 0.03 mg/L and 0.14 mg/L for the outside system.

An increase in nitrate-nitrogen had been recorded. For the inside and outside bins, which received dog faeces, the highest releases of nitrate-nitrogen have been noted. This is due to the additional load of nitrogen. There is also a slight increase for the inside bin 6 and outside bin 6 (no faeces, and no heating or cooling; Table 1). For the outside rig, nitrate-nitrogen reductions were observed for bins 2, 4 and 5. For the outside bins 1, 3, 6 and all inside bins, removal efficiencies were negative (–440% to –62%). In general, systems comprising a geotextile had lower nitrate-nitrogen concentrations.

Microorganism counts varied considerably. For the outside system, total heterotrophic colony forming units (CFU) ranged between 39,000 and 121,000 for the outflow water, and with means of 101,000 and 7,605,000 for the inflow water without and with dog faeces, respectively. For the inside system, the corresponding numbers ranged between 52,000 and 180,000 for the outflow water, and had means of 172,000 and 378,000 for the inflow without and with faeces, respectively.

The microbial activities within the systems mirrored the corresponding carbon dioxide concentrations. The highest concentrations were recorded close to the first two (*i.e.*, the shallowest) sampling points for each bin. This indicates that the most intensive microbial activity takes place around the geotextile [28,29], which was responsible for lower microbial counts within the outflow of most systems during the majority of the monitoring period [3].

5.4. Summary of Conclusions

The data variability of the inside rig was reduced by applying controlled environmental conditions such as a relatively stable temperature. Suspended solids values for outside rigs were on average 100% higher than the corresponding concentrations for the inside rigs, indicating the importance of a relatively high temperature for biodegradation. Ortho-phosphate-phosphorus and ammonia-nitrogen removal rates were very high (up to 95%), and the corresponding absolute concentrations fulfilled European urban wastewater treatment standards.

The microbial activities during high temperature durations were high, which lead to better treatment performances. The elevated carbon dioxide concentrations and corresponding reductions in biochemical oxygen demand are evidence for the increased microbial activity within the sub-base, especially on the geotextile. The cell counts for most bacteria groups with respect to the outflows for systems were usually low.

5.5. Critical Assessment of the Edinburgh Study

The outside rig represents “real” environmental conditions (e.g., pavement systems are surrounded by soil except at their tops), and is therefore more appropriate than the rig operated in the ‘Abertay study’. In comparison, the inside rig allows for modelling due to a reduced degree of freedom (*i.e.* more stable variables such as temperature and humidity) but temperature conditions are unrealistic.

The Edinburgh study was not conducted with the aim to assess the impact of the geotextile on water quality in a statistically sound experimental set-up. However, the findings can be used to assess the indirect influence of the geotextile on some key water quality parameters. During most periods, the presence of a geotextile was beneficial in keeping suspended solids and nitrate-nitrogen concentrations as well as bacteria colony counts relatively low in the outflow. However, the statistical set-up was not optimized to come to conclusive findings regarding the role of the geotextile. Moreover, other important pollutants such as metals and oils were not assessed.

6. Conclusions

Most relevant ecological engineering research on permeable pavement systems has been undertaken in Europe and Northern America. The review of permeable pavement system literature indicates that there are very few studies that directly research the impact of geotextiles within permeable pavement systems on improving the water quality. However, there is an indication that the presence of a suitable geotextile within a permeable pavement system reduces the breakthrough of suspended solids.

The studies covered in detail as part of this paper suggest only a minor statistically insignificant improvement of some water quality parameters (predominantly suspended solids and associated contaminants) when a geotextile is present. Most other parameters such as chloride are virtually unaffected.

A review of the 'Abertay study' on geotextiles within permeable pavement systems indicated that the chosen methodology had its clear limitations and that some findings were inconclusive. In comparison, a review of the 'Edinburgh study' on geotextiles within combined ground source heat and permeable pavement systems shows that the presence of geotextiles makes a minor contribution to improving the water quality.

7. Recommendations for Further Research

The author proposes to conduct a long-term (at least two full years) scientific study with large test rigs located belowground (*i.e.* simulating 'real' conditions). 'Real' runoff spiked with a realistic composition of key pollutants of reasonable concentrations and loads reported for road runoff in the scientific literature should be used within a statistical set-up of different experimental rigs.

There are a few innovations that should be considered at the same time for further research. For example, a heat-bonded geotextile could be used to slow down the release of small oil droplets, and their subsequent transport through the permeable pavement system. Furthermore, geotextiles incorporating trace elements to enhance the degradation of specific contaminants such as oils might be suitable in environments where runoff contains insufficient nutrients.

Considering that this review has identified relevant research predominantly in North America and Northern Europe, new research on geotextiles within permeable pavements should be conducted in areas experiencing warmer and dryer climate. This may include tropical regions in South America, Africa, Asia, Australia and New Zealand suffering from severe flooding during the rainy season. Alternatively, corresponding weather conditions could be simulated in a temperature- and humidity-controlled laboratory or greenhouse.

The overall image of concrete-based permeable pavements could be improved by addressing more ecosystem services variables as part of the new green infrastructure initiative in the UK. For example, more sustainable geotextiles could be selected and permeable pavements could be combined with other SuDS such as infiltration structures and filtration systems including planted filter strips to increase the sustainability rating, improve water quality, and enhance ecology and amenity at the same time.

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